Distribution Characteristics and Accumulation Model for the Coal-formed Gas Generated from Permo-Carboniferous Coal Measures in Bohai Bay Basin, China: A Review

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Abstract: *Coal-formed gas generated from the Permo-Carboniferous coal measures has become one of the most important targets for deep hydrocarbon exploration in the Bohai Bay Basin, offshore eastern China. However, the proven gas reserves from this source rock are remain low to date, and the distribution characteristics and accumulation model for the coal-formed gas are not clear. Here we review the coal-formed gas deposits formed from the Permo-Carboniferous coal measures in the Bohai Bay Basin. The accumulations are scattered, and dominated by middle-small sized gas fields, of which the proven reserves ranging from 0.002 to 149.4×10^{8}m^3 with an average of 44.30×10^{8}m^3 and a mid-point of 8.16×10^{8}m^3. The commercially valuable gas fields are mainly found in the central and southern parts of the basin. Vertically, the coal-formed gas is accumulated at multiple stratigraphic levels from Paleogene to Archaeozoic, among which the Paleogene and Permo-Carboniferous are the main reservoir strata.*

According to the transporting pathway, filling mechanism and the relationship between source rocks and reservoir, the coal-formed gas accumulation model can be defined into three types: "Upward migrated, fault transported gas" accumulation model, "Laterally migrated, sandbody transported gas" accumulation model, and "Downward migrated, sub-source, fracture transported gas" accumulation model. Source rock distribution, thermal evolution and hydrocarbon generation capacity are the fundamental controlling factors for the macro distribution and enrichment of the coal-formed gas. The fault activity and the configuration of fault and caprock control the vertical enrichment pattern.

Key words: *Distribution characteristics of natural gas; accumulation model; coal-formed gas; Permo-Carboniferous coal measures; Bohai Bay Basin*

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1 Introduction

Before the 1970s, the natural gas exploration targets in the Bohai Bay Basin were mainly oil-associated gas, and large-scale gas fields were found less often (Dai et al, 2015). The coal-formed gas theory has been applied to natural gas exploration in China since the late 1970s, which greatly promoted the development of Chinese natural gas industry, especially the exploration of the Late Paleozoic relative coal-formed gas As for the Bohai Bay Basin, several large-scale gas fields, such as Wenliu Gas Field in Dongpu Depression (Jiang et al., 2008; Zeng et al., 2013), Suqiao-Wenan Gas Field in Jizhong sub-basin (Liu et al., 2017), Gubei Gas Field in Jiyang sub-basin (Zhang et al., 2009b; Zhao et al., 2015) have been discovered, confirming the contribution of the Permo-Carboniferous coal-measured source rocks. Previous studies illustrated that Permo-Carboniferous source rocks can be viewed as excellent gas source rocks with enormous hydrocarbon generation potentials (Jin et al., 2009; Zhu et al., 2010a; Zhu et al., 2010b; Zhang et al., 2014; Ge & Bi, 2016). However, there is few large coal-formed gas fields that has been found up to now (Fang et al., 2016). The degree of exploration of coal-formed gas is still low. In recent years, the exploration of coal-formed gas from Permo-Carboniferous made great success in the Hugu 2 well and Fang 2 well in Dongpu Depression, and the Zhong 1502 well in Qikou Depression (Li et al., 2015; Guo et al., 2017; Guo et al., 2013), which prompted the re-attention of the exploration of Permo-Carboniferous relative coal-formed gas. Significant differences exist in the coal-formed gas accumulation conditions, distribution characteristics and accumulation models in different areas of the Bohai Bay Basin (Cheng et al., 2002; Fu et al., 2002; Du et al., 2003; Zhang et al., 2003; Jiang et al., 2008; Wang et al., 2008; Jiang et al., 2009; Li et al., 2015; Liang et al., 2016; Guo et al., 2017; Liu et al., 2017; Hu et al., 2018; Qu et al., 2018). However, studies on the summary and comparison of the coal-formed gas accumulation conditions, distribution patterns and the accumulation models of the whole basin from a macro perspective have not been carried out yet, which has an adverse effect on the exploration success rate. Based on the coal-formed gas exploration practice and previous research results of the Bohai Bay Basin, the hydrocarbon generation characteristics of the Carboniferous-Permian source rocks is discussed, and systematic study is carried out on the distribution pattern, accumulation model, and main controlling factors of the coal-formed gas derived from the Permo-Carboniferous coal measures.

2 Geological Settings and Source Rock

2.1 Geological settings

The Bohai Bay Basin is located in eastern China with a total area of 20×10^5 km^2.It is a Mesozoic-Cenozoic sedimentary basin overlapping on the Neoproterozoic-Paleozoic platform. The basin is subdivided into 7 independent sub-basins and 4 uplifts, namely Liaohe, Bozhong, Jiyang, Huanghua, Jizhong, Linqing, Changwei sub-basins, and the Chengning, Neihuang, Cangxian and Xingheng uplifts (Peng et al., 2010) (Fig1).

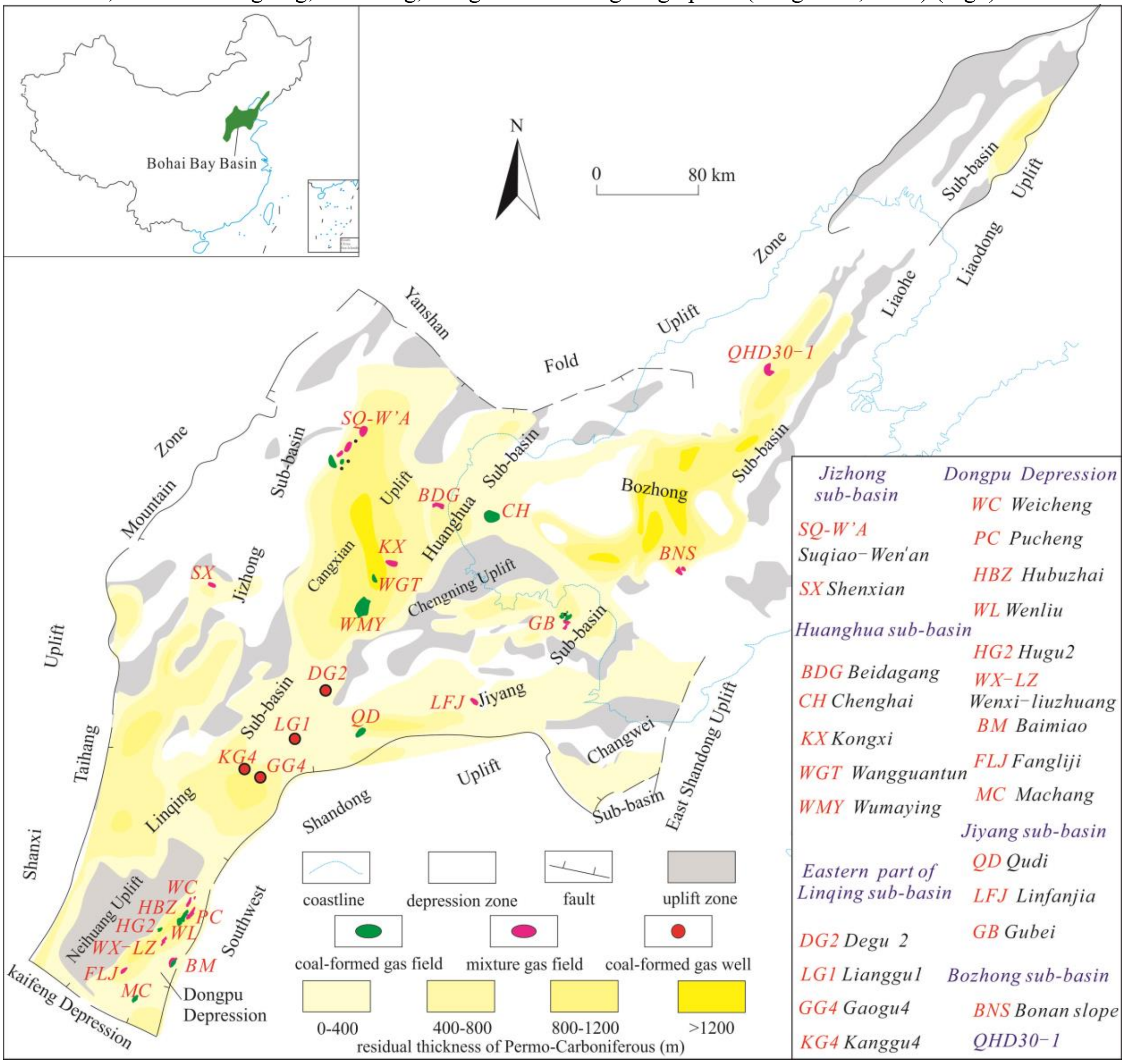


Fig. 1. Map showing the tectonic units of the Bohai Bay Basin, current distribution of coal-formed gas fields and residual thickness of Carboniferous-Permian (modified from Zhang et al., 2009a).

China basemap after China National Bureau of Surveying and Mapping Geographical Information.

From the Paleozoic to Cenozoic, the Bohai Bay Basin has experienced complex tectonic events which can be divided into four different stages (Zhou et al., 2007; Peng et al., 2010; Zuo et al., 2015), including the regional subsidence and uplift stage (middle-late Ancient to Paleozoic), differential subsidence and uplift stage (Mesozoic), syn-rifting stage (Paleogene), and post rifting stage (Neogene) (Peng et al., 2010; Jiang et al., 2015; Jiang et al., 2017). The tectonic movements, especially the movement during Mesozoic and Cenozoic, varied in different regions of the Bohai Bay Basin. Corresponding to the staged tectonic evolution, the sedimentological evolution of the Bohai Bay Basin comprises four major stages as well, including (1) a stable marine carbonate platform in the Early Paleozoic, (2) mixed marine and continental sedimentation in the Late Paleozoic, (3) an intracontinental lake basin depression filled with coarse clastic rocks in the Early Mesozoic, and (4) rifting and post-rifting basin in the Late Mesozoic and the Cenozoic (Qi and Yang, 2009). The complete sequence of stratigraphy in the basin constitutes a series of oil & gas generation–preservation–cover sequences (Fig.2).

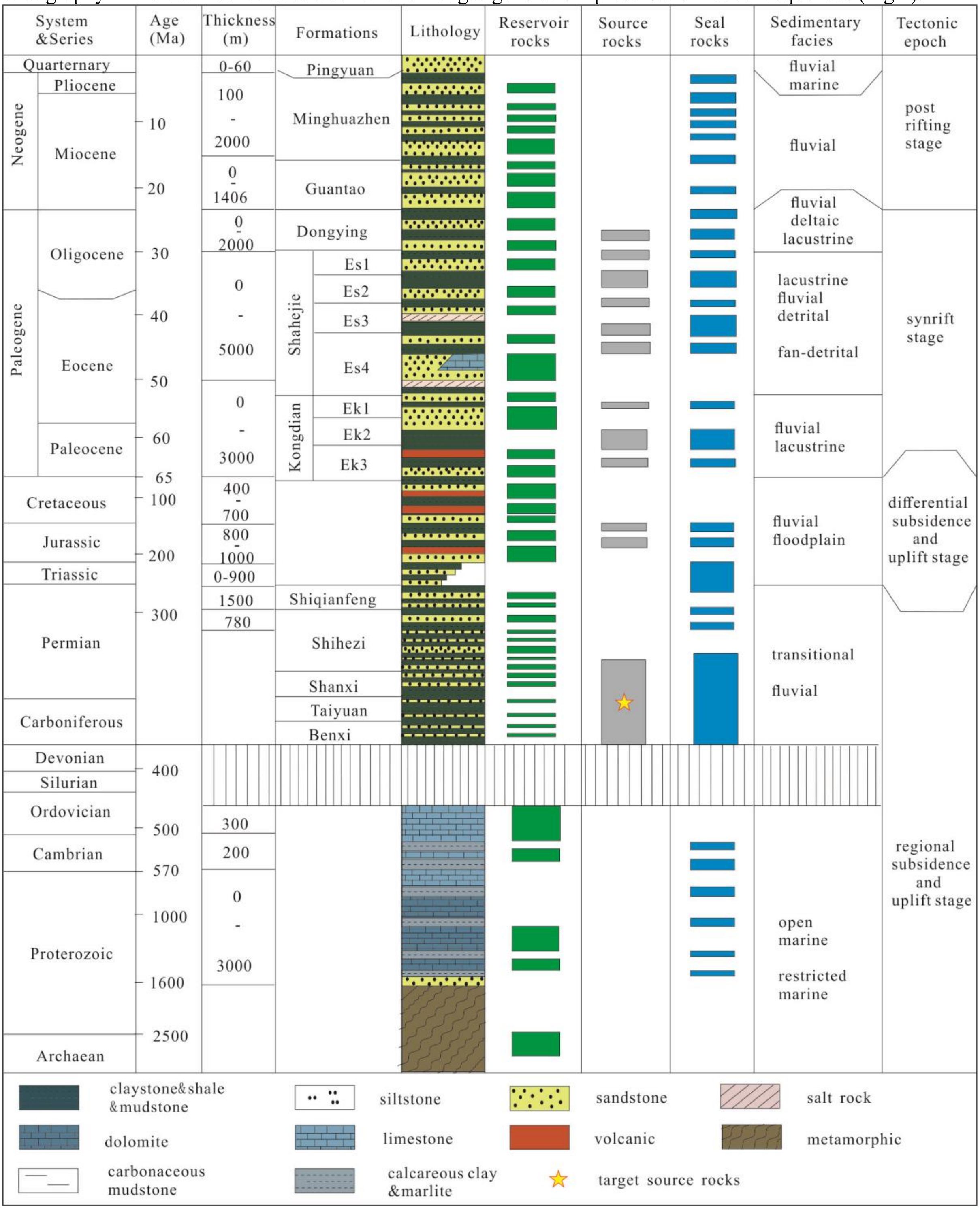


Fig. 2. Schematic stratigraphy and source rocks-reservoir-seal relationship for the Bohai Bay Basin (modified from Zhang et al., 2009a).

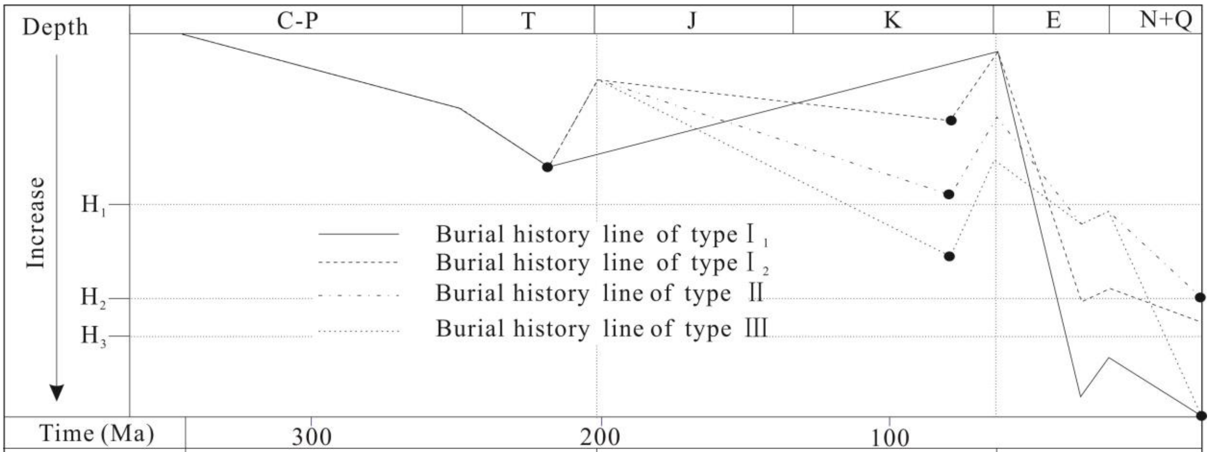
Multiple sets of source rocks formations were developed in the Bohai Bay Basin (Chang, 1991) (Fig. 1B), but most of them are oil-prone, such as the Ordovician marine source rocks, and the lacustrine source rocks of Kongdian Formation, Shahejie Formation, Dongying Formation of Paleogene system. The Carboniferous-Permian coal measures and the Jurassic-Cretaceous coal measures are gas prone source rocks (Jiang et al., 2016). The Jurassic-Cretaceous coal measures are proven to be of poor quality according to the latest resource evaluation data. Most of proven natural gas in the Bohai Bay Basin were generated from Carboniferous-Permian coal measures (Huang et al., 2010).

There are many stratigraphic levels can be served as effective reservoirs in the Bohai Bay Basin, including the Cenozoic clastic rocks, Mesozoic clastic rocks and volcanic rocks, Permo-Carboniferous clastic rocks, Ordovician carbonate rocks, Middle-upper Archaic carbonate rocks, and Archean metamorphic rocks (Fig2). As for caprocks, except for the widely distributed regional caprocks(Carboniferous coal measures, the mudstone layers at the top of Permian system, the mudstone layers at the bottom of the Triassic, the Jurassic coal measures, and the mudstone layers in the first and third member of Shahejie Formation of Paleogene system), there are also many mudstone intervals between reservoir rocks can be acted as seals under certain conditions.

2.2 Source rock

Influenced by the zoning of tectonic evolution, the Permo-Carboniferous strata incompletely covered the basin with the thickness from 0-1300 m, and many lacunas occurred in certain parts. The residual thickness of the strata in different tectonic units of the basin are different. The areas covered with residual Permo-Carboniferous strata in the basin can be divided into six parts based on the residual thickness features (Zhu et al., 2010b), including the northeast of Jizhong sub-basin, the south of Jizhong sub-basin, Huanghua sub-basin, Dongpu Depression, Jiyang sub-basin and the east of Linqing sub-basin. Specifically, the Permo-Carboniferous strata fully developed in the northeast of Jizhong sub-basin, the middle and south of Huanghua sub-basin, Dongpu Depression, and the east of Linqing sub-basin, with the maximum residual thickness of 1300m, 1200m, 1100m and 900m, respectively (Fig. 1). The thickness of effective source rocks in these areas ranges from 200m to 250m. By contract, the Permo-Carboniferous in the Jiyang sub-basin is incomplete, with residual thickness ranging from 200 to 600m. The effective source rocks in the Jiyang sub-basin are sporadic distributed with the thickness of 100-150m (Li, 2006). Overall, the original widely-distributed Permo-Carboniferous coal measures were seriously eroded and finally rifted into approximately 40 isolated source rock kitchens with depressions as unit.

Generally, the burial and thermal history of Permo-Carboniferous source rocks in the basin can be divided into three stages, including the Indo-Chinese epoch, Yanshan epoch, and Himalayan epoch, respectively. These three stages are corresponding to three possible hydrocarbon generation stages. However, the burial and thermal evolution history of source rock varies in different regions due to the differential tectonic evolution, leading to diverse hydrocarbon generation evolution history (Peng et al., 2010; Qiu et al., 2010; Zhu et al., 2010b; Zuo et al., 2011; Qiu et al., 2016; Qu et al., 2018). The thermal evolution and hydrocarbon generation characteristics of the target source rocks during the Indo-Chinese epoch are basically similar all over the basin (Zhu et al., 2010b), demonstrating the weakly hydrocarbon generating with low-mature stage. As for the Himalayan epoch which is the main hydrocarbon generation period, all the depressions in the basin have entered the stage of maturity to over-mature thermal status. However, the differentiation of hydrocarbon generation mainly occurred during the Yanshan period. Based on the hydrocarbon generation features of the Permo-Carboniferous source rocks in Yanshan epoch, all the depressions in the Bohai Bay Basin can be classified into four types, including Type I_1, Type I_2, Type II and Type III. As for the group of type I_1 and I_2, there was no hydrocarbon generation occurred during the Yanshan epoch resulting from the burial history of this period showing as “Erosion” (type I_1) or “Undercompensated deposition” (type I_2). With regard to type and type III, there are three hydrocarbon generation periods occurred in three burial and thermal stages correspondingly. The difference between the two is that the former one experienced a weak hydrocarbon generation in the Yanshan period while the latter does not (Fig 3).



Tectonic stage		Indo-Chinese	Yanshan	Himalayan
I_1	Burial history	Deposition	Erosion	SCD
	TES	Low-mature	Low-mature	Mature to over-mature
	HGS	1st HG	No HG	2nd HG
I_2	Burial history	Deposition	Undercompensated Deposition	SCD
	TES	Low-mature	Low-mature	Mature to High-mature
	HGS	1st HG	No HG	2nd HG
II	Burial history	Deposition	Weak Compensated Deposition (WCD)	WCD
	TES	Low-mature	Low-mature	Mature
	HGS	1st HG	2nd HG (Weakly)	3rd HG
III	Burial history	Deposition	Strong Compensated Deposition (SCD)	SCD
	TES	Low-mature	Mature	Mature to over-mature
	HGS	1st HG	2nd HG (Strongly)	3rd HG

Fig. 3. The classification of depressions based on the thermal evolution and hydrocarbon generation features of Permo-Carboniferous source rocks in the Bohai Bay Basin.

H_1, H_2, H_3 represent the threshold depth values of the mature stage, the high mature stage and the over mature stage, respectively. SCD=Strongly compensated deposition, WCD=Weakly compensated deposition, TES=Thermal evolution stage, HGS=Hydrocarbon generation status.

The types of over 40 depressions in the Bohai Bay Basin have been summarized, and the result shows that the northern part of the Jizhong sub-basin, Huanghua sub-basin, and the central part of Bozhong sub-basin are dominated by type II depressions; the depressions in the Linqing sub-basin and Jiyang sub-basin mainly belong to type III; a few depressions belong to type I, including the Dongpu Depression, Baxian Depression, Banqiao Depression, Kongdian Depression and Nanpu Depression (Fig. 4).

Fig. 4. Lateral distribution of different types of depressions classified by thermal evolution and hydrocarbon generation history for the Permo-Carboniferous source rocks in Bohai Bay Basin.

3 Distribution Characteristics

3.1 Lateral distribution

The natural gas formed from the C-P coal measures were found in Jizhong, Huanghua, Linqing, Jiyang and Bozhong sub-basins. The structural belts where the coal-formed gas accumulated include the Suqiao-Wen'an slope zone in Jizhong sub-basin (Liu et al., 2017), the Gubei buried hill (Zhang et al., 2009b), Linfanjia low-uplift zone and the Qudi horst zone in Jiyang sub-basin (Du et al., 2003), the Gaogu4 and other coal-formed gas wells in the eastern part of Linqing sub-basin (Liang et al., 2016), the central uplift belts such as Wenliu, Hubuzhai, Machang, and the slope zones such as Baimiao, Fangliji, Huzhuangji in Dongpu Depression (Tan et al., 2017), the Wumaying, Kongxi, Chenghai and Beidagang buried hills in Huanghua sub-basin (Guo et al., 2013), and the QHD30-1 and BZ28-1 low-uplift belt in Bozhong sub-basin (Zhou et al., 2006) (Fig.1). The existence of numerous faults made the possibility of mixing the oil-type gas generated from the lacustrine mudstone of Paleogene Shahejie Formation and the coal-formed gas derived from Permo-Carboniferous coal measures. Therefore, the natural gas deposits related to Permo-Carboniferous coal measures in the basin now appears in two forms, including the mixed gas pools (coal-formed gas and oil-type gas) and the coal-formed gas pools (Huang et al., 2010). Among them, the number of mixed gas pools accounts for over 60%. These two forms of gas deposits are both regarded as coal-formed gas in this paper, rather than being distinguished.

Generally, the distribution of the gas fields generated from the Permo-Carboniferous source rocks in the Bohai Bay Basin is relatively scattered and most of them are small in scale. The large-scale gas fields are mainly distributed in the central and southern parts of the basin, including the northeastern part of Jizhong sub-basin, the central and southern parts of the Huanghua sub-basin and the Dongpu Depression. The medium-sized gas fields include the Suqiao-Wen`an gas field in the Jizhong sub-basin, the Wenliu gas field and the Baimiao gas field in the Dongpu Depression with the proven reserves of 129.42×10^8 m^3, 154.12×10^8 m^3 and 126.23×10^8 m^3, respectively (Fang et al., 2016). The rest are mostly small-sized gas fields, such as the Machang gas field and the Chenghai gas field. In certain areas, only a few coal-formed gas wells were found. For example, only seven coal-formed gas wells were successfully drilled in the eastern part of Linqing sub-basin, and among them the Gugu 4 well is the main source of production with the cumulative gas production of only 20×10^4 m^3 (Liang et al., 2016).

3.2 Vertical distribution

Vertically, the coal-formed gas generated from Permo-Carboniferous in the Bohai Bay Basin is distributed at multiple stratigraphic levels and characterized by differential enrichment. This kind of gas has been discovered in Archean (Ar), Ordovician (O), Carboniferous-Permian (C-P), Mesozoic (Mz), Paleogene and Neogene of Cenozoic (E+N) in the basin. Among them, the gas is mainly produced in the Ordovician (O), Carboniferous-Permian (C-P) and Shahejie Formation (Es) of Paleogene, with the proportion of the proven reserves about 8%, 40%, 50%, respectively (Fig. 5A) and the number of gas reservoirs accounting for 22%, 33% and 35%, respectively (Fig. 5B).

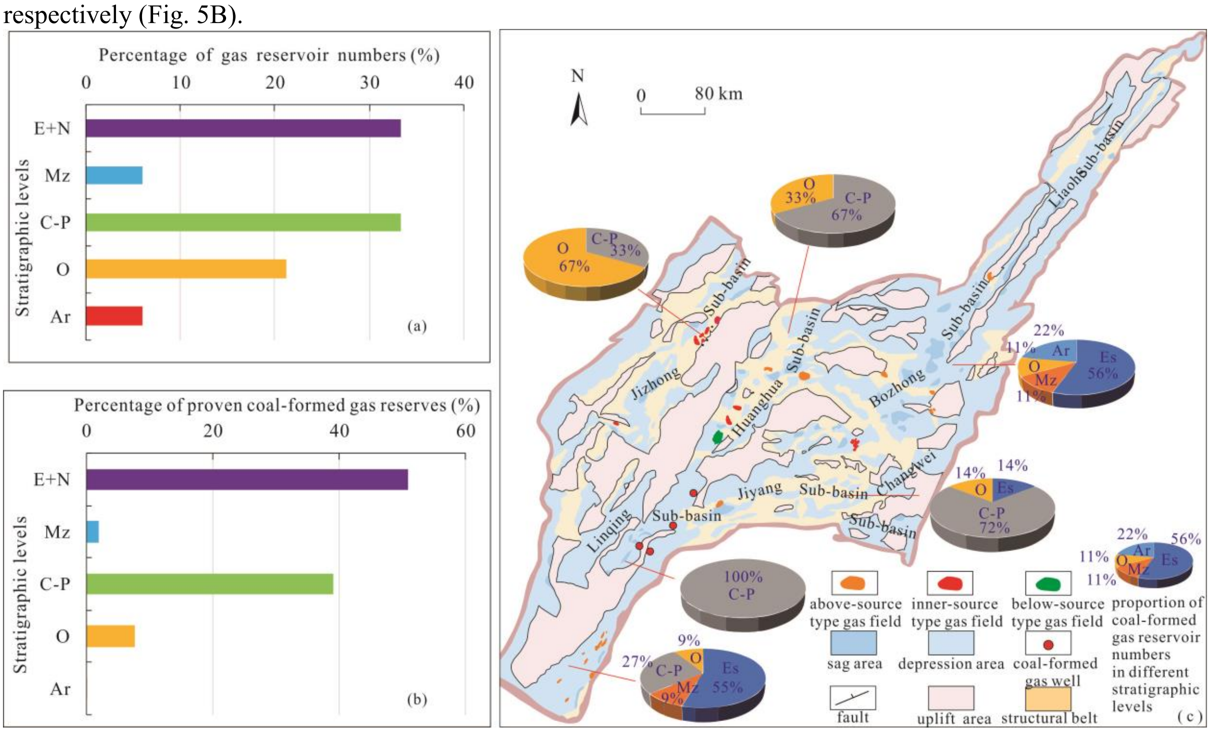


Fig. 5. Vertical distribution of coal-formed gas generated from Permo-Carboniferous in the Bohai Bay Basin.

(a) Percentage of gas reservoir numbers in different stratigraphic levels; (b) Proportion of proven coal-formed gas reserves in different stratigraphic levels; (c) Map showing macroscopic differences of vertical reservoir strata of coal-formed gas in different sub-basins, in which the pie chart illustrates the percentage of coal-formed gas reservoir numbers in different stratigraphic levels.

From a macro perspective, there are large differences in the main coal-formed gas reservoir strata between different sub-basins. The coal-formed gas in the northeastern part of the Jizhong sub-basin, the Huanghua sub-basin, the eastern Linqing sub-basin and the Jiyang sub-basin are mainly enriched in Permo-Carboniferous and Ordovician, with the number of gas reservoirs taking up over 80%. However, the coal-formed gas in Bozhong sub-basin and the Dongpu Depression are accumulated in multiple stratigraphic levels, among which the Shahejie Formation hold the most gas reservoirs (the proportion reaches over 50%) (Fig. 5C). From a micro perspective, even though the coal-formed gas of any one gas field is generally enriched in multiple stratigraphic levels vertically, the degree of enrichment of different levels is obviously different and usually dominated by one level. Taking the Wenliu gas field as an example, coal-formed gas is distributed in the Es4, Mz and Permo-Carboniferous, but More than 90% of the total reserves of the gas field are accumulated in the Es4 (Jiang et al., 2008).

According to the spatial relationship between the coal-formed gas deposits and the effective source rocks (the whole Permo-Carboniferous strata below the "gas window"), the vertical enrichment characteristics of coal-formed gas fields in the Bohai Bay Basin can be classified into three patterns, namely Above-source pattern (pattern A), Inner-source pattern (pattern B) and Below-source pattern (pattern C) (Fig. 6). As for the "above-source pattern", the coal-formed gas deposits are mainly accumulated above the effective source rocks. Gas fields of this pattern, like Wenliu, Chenghai and Beidagang, are mainly distributed in the steep slope zones, the central uplift zones and the uplifts between depressions. Specifically, this pattern can be subdivided into two categories, including the “Above-source, Cenozoic enrichment pattern” (pattern A_1) and the “Above-source, Paleozoic enrichment pattern” (pattern A_2). The Inner-source pattern represents the group of which the coal-formed gas deposits are located within the hydrocarbon-generating strata. The gas fields of this pattern, such as Suqiao-Wen'an, Gubei, Gaogu 4, and Hugu 2., are widely distributed in the slope zones. The Below-source pattern refers the deposits which are situated below the effective source rocks, and the gas fields of this pattern tend to be distributed in the sag zone.

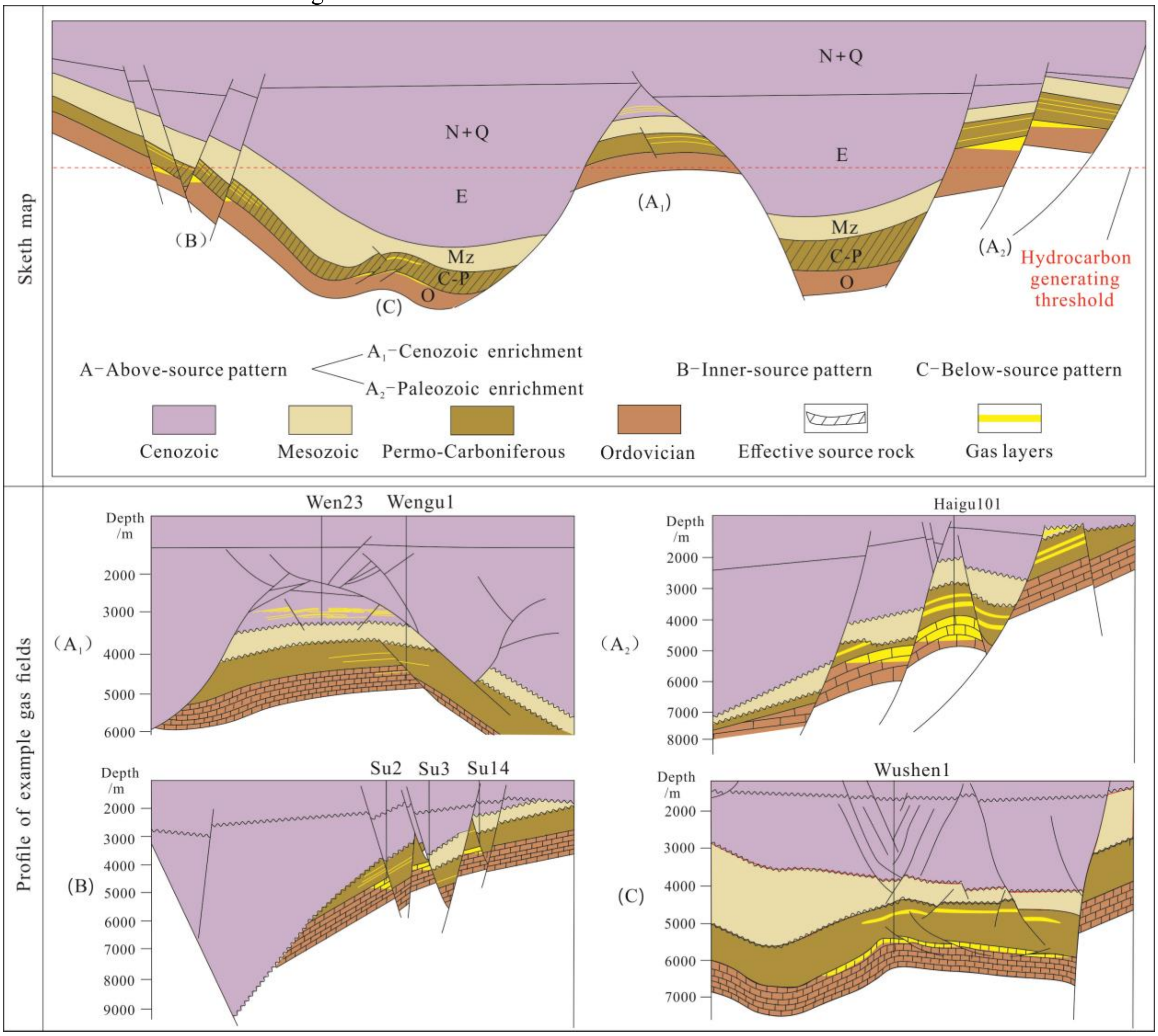


Fig. 6. Schematic and example profiles of the vertical enrichment pattern classification of coal-formed gas fields in the Bohai Bay Basin.

4 Coal-formed Gas Accumulation Model

The coal-formed gas generated from the Permo-Carboniferous in the Bohai Bay Basin is characterized by diversified migration and accumulation forms according to the collection of previous study (Table 1). There are certain correlations between the structural locations, vertical enrichment patterns, transporting pathways and filling mechanism of the gas fields. In this case, the accumulation models of coal-formed gas in the Bohai Bay Basin were established (Fig.7), namely "fault-transported, vertical split charging, above-source accumulation" model, "sand body-transported, lateral docking charging, inner-source accumulation" model, and "fracture-transported, covering contact charging, below-source accumulation" model. In order to make these models easy to understand, the systematical descriptions on the natural gas source, transport system, migration path and accumulation process of each model were carried out by taking the Wenliu gas field, the Gubei gas field and the Wumaying Gas Field as typical examples.

Table1 The basic reservoir-forming characteristics of coal-formed gas fields in the Bohai Bay Basin, including the structural locations, vertical enrichment types, transport and filling methods of gas fields.

Sub-basin	Gas field	Structural belt	Reservoir strata	Natural gas genesis type	Vertical enrichment pattern	Main transport pathway	Filling mechanism	Data source
Huanghua	Beidagang	Uplift zone	C-P*、O	CFG, MG	A_2	Fault	VSC	UR
Huanghua	Koucun	Uplift zone	C-P*、O	CFG, MG	A_2	Fault	VSC	UR
Bozhong	QHD30-1	Uplift zone	Es*、Mz	MG	A_1	Fault	VSC	Zhou et al, 2006
Huanghua	Chenghai	Steep slope	C-P*、O	CFG, MG	A_2	Fault	VSC	Fu et al, 2013
Huanghua	Wangguantun	Steep slope	C-P	CFG, MG	A_2	Fault	VSC	UR
Linqing	Baimiao	Steep slope	Es*、C-P	CFG, MG	A_1	Fault	VSC	UR
Linqing	Fangliji	Steep slope	Es*	CFG, MG	A_1	Fault	VSC	Guo et al, 2017
Linqing	Wenliu	Central uplift zone	Es*、C-P	CFG	A_1	Fault	VSC	Jiang et al, 2008
Linqing	Hubuzhai	Central uplift zone	Es*、Mz、C-P	CFG	A_1	Fault	VSC	Li et al, 2008
Linqing	Machang	Central uplift zone	Es*、C-P	CFG	A_1	Fault	VSC	UR
Linqing	Pucheng	Central uplift zone	Es*	MG	A_1	Fault	VSC	Xia et al, 2002
Linqing	Weicheng	Central uplift zone	Es*	MG	A_1	Fault	VSC	UR
Jiyang	Qudi	Central uplift zone	Es*	MG	A_1	Fault	VSC	Du et al, 2003
Jizhong	Shenxian	Central uplift zone	O*	MG	A_2	Fault	VSC	UR
Bozhong	Bonan slope	Gentle slope	Es*	MG	B	Fault	LDC	UR
Jizhong	Suqiao-Wen'an	Gentle slope	C-P*、O	CFG, MG	B	Sand body	LDC	Liu et al, 2017
Jiyang	Gubei	Gentle slope	C-P*	CFG, MG	B	Sand body	LDC	Zhang et al, 2009b
Linqing	Hugu2	Gentle slope	C-P*	CFG	B	Sand body	LDC	Li et al, 2015
Linqing	Gaogu4	Gentle slope	C-P*	CFG	B	Sand body	LDC	Liang et al, 2016
Huanghua	Kongxi	Gentle slope	C-P*	CFG	B	Sand body	LDC	Cheng et al, 2002
Huanghua	Wumaying	Sag zone	C-P、O*	CFG	C	Fractures	CCC	Fu et al, 2002

CFG=Coal-formed gas, MG=Mixed-gas, VSC= Vertical split charging, LDC= lateral docking charging, CC=Covering contact charging, UR=Unpublished report. * represents the major reservoir strata.

4.1 "Upward migrated, fault transported gas" accumulation model

The coal-formed gas fields with this accumulation model are mainly distributed in the horst zones controlled by large-scale faults, such as the central uplift belt in a depression, the steep slope belt and the between-depression uplift belt. These areas are generally separated with the effective source rocks (Table 1). Therefore, the fault linking up the upper reservoir-cap rock system and the lower effective source rocks is the essential factor for the coal-formed gas migration and accumulation. The gas flowed separately into the sand bodies during the vertical transporting process along faults（Fig. 7A）. For these coal-formed gas deposits, faults can also be acted as the transporting pathways of the hydrocarbon generated from the lacustrine Paleogene source rocks. Therefore, the gas field would probably be a mixed-gas field due to the mixing of the two types of gas. The lateral sealing of faults and the differences in charging periods of the two types of gas are the keys to determine whether a mixed gas reservoir would be formed.

The Wenliu gas field, a semi-anticline with the background of bedrock dome, is located in the central uplift zone of Dongpu Depression, and adjacent to the Qianliyuan and Haitongji sags at the east and west side. Two boundary basement faults named Wenxi and Wendong fault exist in this area. The natural gas is accumulated in the fourth member of Shahejie Formation of Paleogene (Es4) and the Permo-Carboniferous. According to the analysis of the origin and migration paths (Jiang et al., 2008), the natural gas was formed from the Permo-Carboniferous coal-measured source rocks in the Qianliyuan sag, flowing separately to the sandstone reservoir of the Es4 and Permo-Carboniferous while vertically migration along the Wendong fault. The salt caprocks of the lower Es3 formation covering the Es4 sandstone reservoir is the regional caprock providing an excellent sealing condition for coal-formed gas accumulation. The salt rock of upper and middle of Es3 formation formed a good lateral sealing condition (Fig. 7A). However, for the Baimiao gas field which is also characterized by “fault-transported, vertical split charging, above-source accumulation” (Cui et al., 2012), the lateral sealing of the trap which is side-controlled by Duzhai fault is poor, thus the hydrocarbon generated from the Paleogene source rocks could migrate laterally through the fault to the trap and be mixed with the coal-formed gas.

There are many other gas fields belonging to this type of accumulation model, including the Hubuzhai, Machang, Baimiao, Fangliji, Pucheng-Weicheng gas fields in Dongpu Depression, the Beidagang, Chenghai, Wangguantun, Koucun gas fields in Huanghua sub-basin, the Qudi gas field in Jiyang sub-basin, and the QHD30-1 gas field in Bozhong sub-basin.

4.2 "Laterally migrated, sandbody transported gas" accumulation model

As for the gas fields of this accumulation model, most of them are located in the gentle slope zones developing with none or just a small number of small-scale faults. The coal-formed gas in these gas fields is mainly accumulated in Permo-Carboniferous, and the interconnected sand bodies are the essential factors for the migration of the coal-formed gas (Table 1). In general, the Permo-Carboniferous is partly staggered by the small-scale faults. These faults might lead to the effective source rock of Carboniferous-lower Permian laterally docking with the sandstone reservoirs of upper Permian, and the connect part could be served as the “effective hydrocarbon-supplying window” for the coal-formed gas filling into the trap（Fig. 7B）. In addition, the coal-formed gas fields of this model would probably be in contact with the matured source rocks of Paleogene through the unconformity surface and faults, thus the oil-type gas might migrate into the traps by those paths. Therefore, the deposits are usually characterized by "mixed gas accumulation, zoning distribution".

This type of gas reservoir is represented by the Gubei gas fields in Jiyang Sub-basin. The Gubei gas field, a Paleozoic buried hill controlled by the Guxi fault, is located in the central part of the Zhanhua Depression, bordered by the Bonan sag in the west and the Gubei sag in the east. Three genetic types of natural gas, namely coal-formed gas, oil-type gas and mixed gas, were accumulated in Ordovician and Permo-Carboniferous reservoirs in this area according to the previous studies. The coal-formed gas was derived from the Permo-Carboniferous source rocks in the deep slope zone on the direction of Gubei sag, and migrated from the north to the south through the sand bodies cut by faults. The oil-type gas came from the Paleogene source rocks in Bonan sag, migrated across the Guxi fault and unconformity, and finally formed a “coal-formed gas-mixed gas-oil-type gas” zoning distribution from the east to the west (Wang et al., 2008).

In addition, some other gas fields, such as the Suqiao-Wen'an gas field in the Jizhong sub-basin, the Hugu 2 gas field in Dongpu Depression, the Gaogu 4 gas field in the eastern part of Linqing sub-basin, and the Kongxi gas field in Huanghua sub-basin, all belong to this type of accumulation model.

4.3 "Downward migrated, sub-source, fracture transported gas" accumulation model

Coal-formed gas deposits accumulated with this model are mainly distributed in the low-uplifts or the basement anticlines in the deep sag zones (Table 1). In general, there are few faults developing in this kind of gas fields, thus the Permo-Carboniferous are slightly or not destroyed by faults. It is less probably for the effective source rock of Carboniferous-Lower Permian to be laterally adjacent to the sandstone reservoirs of upper Permian. The source rocks of Lower Carboniferous directly covering the Ordovician carbonate weathering crust formed a favorable source-reservoir-cap assemblage, and the coal-formed gas generated from the upper source rocks was directly charged into the lower reservoir rocks (Fig. 7C).

This type of gas fields is represented by the Wumaying Gas Field in Huanghua sub-basin. The Wumaying gas field, an ancient anticline firstly forming in the Yanshan epoch and adjusting in Paleogene, is located in the deep sag zone of Nanpi Depression in the southern part of Huanghua sub-basin. The natural gas was generated from the Permo-Carboniferous source rocks and mainly accumulated in the Ordovician weathering crust (Zhang et al., 2003). The reverse structure provides the ancient trap, and the existence of the reverse fault can also make the lateral contact condition for the Permo-Carboniferous source rocks and the Ordovician reservoir rocks. The fault-fracture system at the top of the weathering crust provides conditions for episodic hydrocarbon expulsion (Shi et al., 2009). The coal-formed gas could be filled directly into the adjacent Ordovician carbonate weathering crust (Fig. 7C).

The formation of gas deposits with this model are controlled by the quality of reservoirs and the dynamic condition of hydrocarbon filling. At present, there is few gas reservoirs of this model discovered in the Bohai Bay Basin. The area where the Ordovician weathering crust reservoirs are well-developed and the hydrocarbon generation intensity is high might be favorable accumulation areas for this type of gas fields.

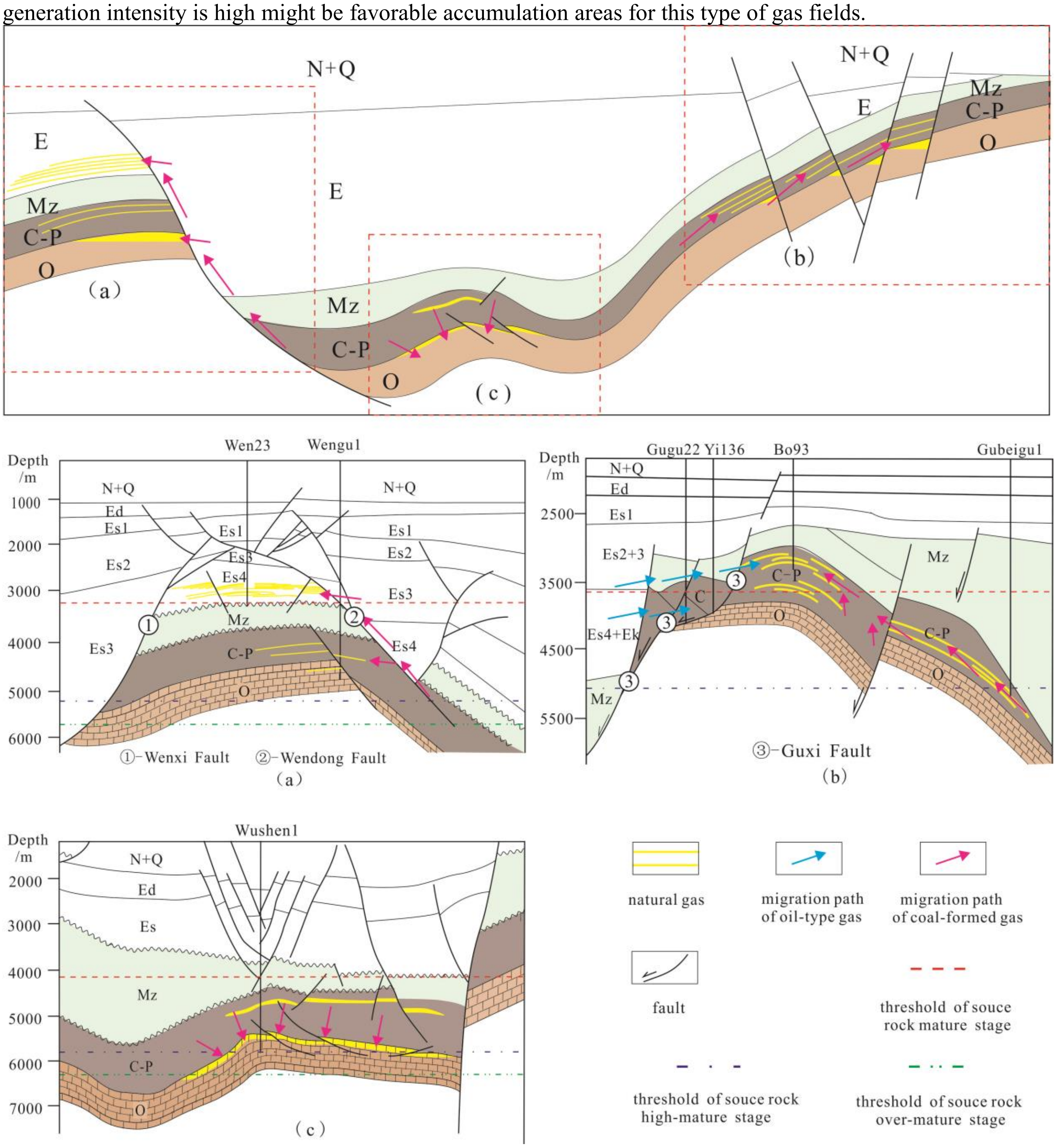


Fig. 7. Schematic diagram and example profiles of coal-forming gas accumulation models in the Bohai Bay Basin.

5 Main Controlling Factors of Coal-formed Gas Distribution

5.1 The distribution, thermal evolution and hydrocarbon-supplying capacity of the source rocks control the macro distribution and enrichment degree of coal-formed gas

On one hand, the macroscopic distribution of coal-formed gas in the Bohai Bay Basin is limited by the distribution of residual Permo-Carboniferous strata, leading to the absence of the coal-formed gas deposits in the areas without Permo-Carboniferous, such as southwestern part of Jizhong sub-basin as well as Liaohe sub-basin. On the other hand, the distribution and the hydrocarbon generation intensity of effective source rocks have important controlling effects on the distribution and enrichment of natural gas related to Permo-Carboniferous coal measures. More than 90% of the natural gas fields related to Permo-Carboniferous were found in the areas where the hydrocarbon generation intensity (HGI) was greater than 100×10^4 t/km^2 (Fig. 8). Therefore, the traps near the zone with HGI over 100×10^4 t/km^2 are advantageous sites for the accumulation of coal-formed gas from the Permo-Carboniferous.

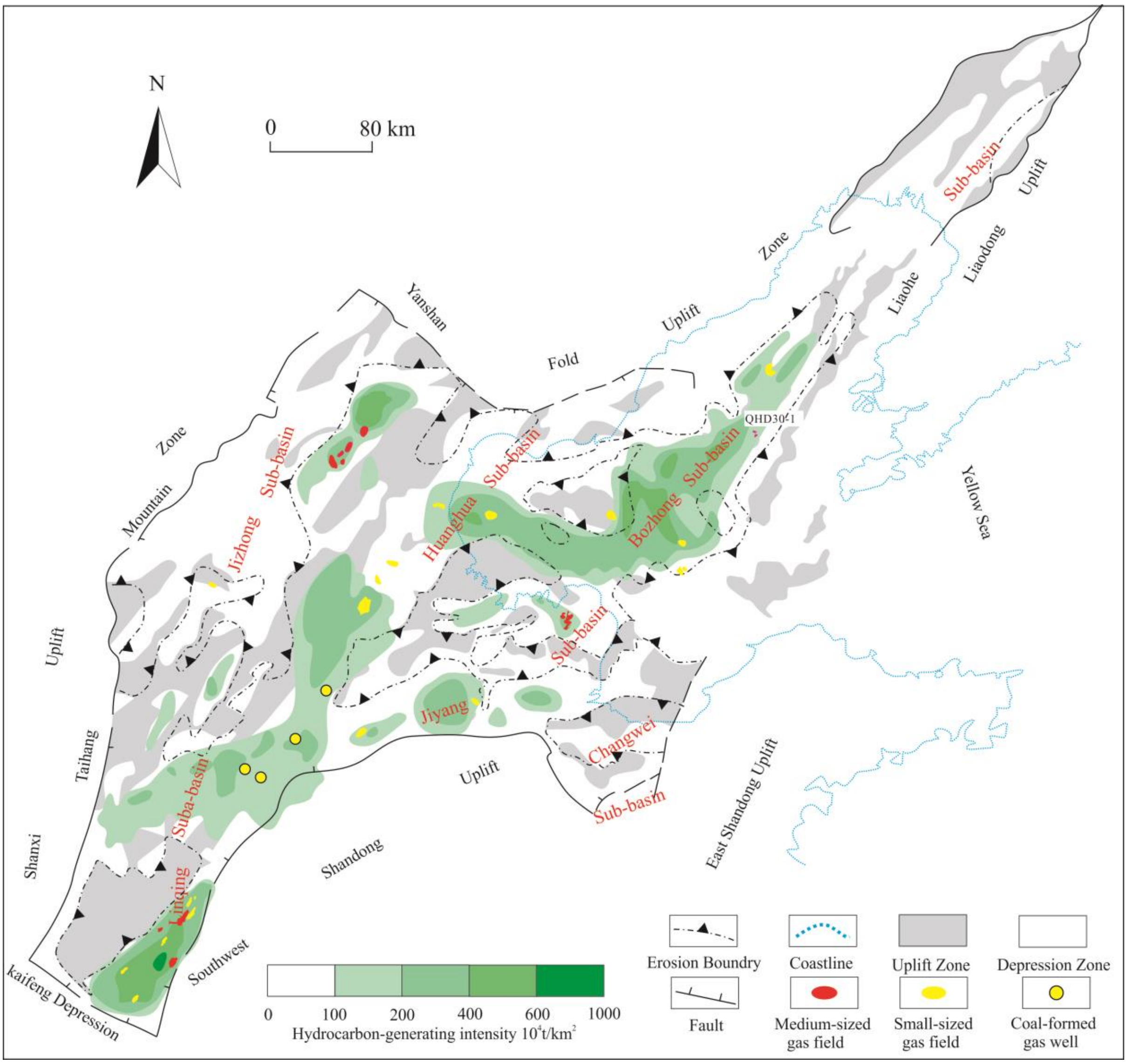


Fig. 8. Map showing the relationship between the lateral distribution of the coal-formed gas derived from Carboniferous-Permian and the hydrocarbon generation intensity of the source rocks in the Bohai Bay Basin according to Zhang et al. (2009a).

In addition, based on the resource evaluation data collection of nearly 40 depressions in the basin, it can be found that the type I depression have a relatively high hydrocarbon generation proportion in the Himalayan epoch (approximately 80%), and a small amount of hydrocarbons generation in the Yanshan epoch and the Indo-Chinese epoch. In contrast, the type III groups hold a significantly low hydrocarbon generation proportion (about 0–30%) in the Himalayan epoch and a relatively high proportion (about 30~50%) in the Yanshan epoch (Fig.9). Over 80% of the total proven reserves of coal-formed gas from Permo-Carboniferous in the Bohai Bay Basin are discovered in the depressions of type I, but there are just a few numbers of coal-formed gas have been proven in the type II and type III depressions. It might be because the Bohai Bay Basin has experienced strong fault activities during the Mesozoic and Cenozoic, which may result in a large loss of hydrocarbons generated in the early stages of the type III depressions. The type I groups which is characterized by late hydrocarbon generation, are more conducive to the preservation of coal-derived gas and have the potential to form large and medium-sized gas fields. However, not all the depressions of type I are enriched in coal-formed gas. The depressions with larger amount of cumulative hydrocarbon generation and the thermal evolution of type I, such as Dongpu and Baxian Depression, tend to contain larger coal-formed gas reserves than the others, revealing that the thermal evolution type of the depression and cumulative hydrocarbon generation amount jointly control the coal-formed gas enrichment degree of the depression.

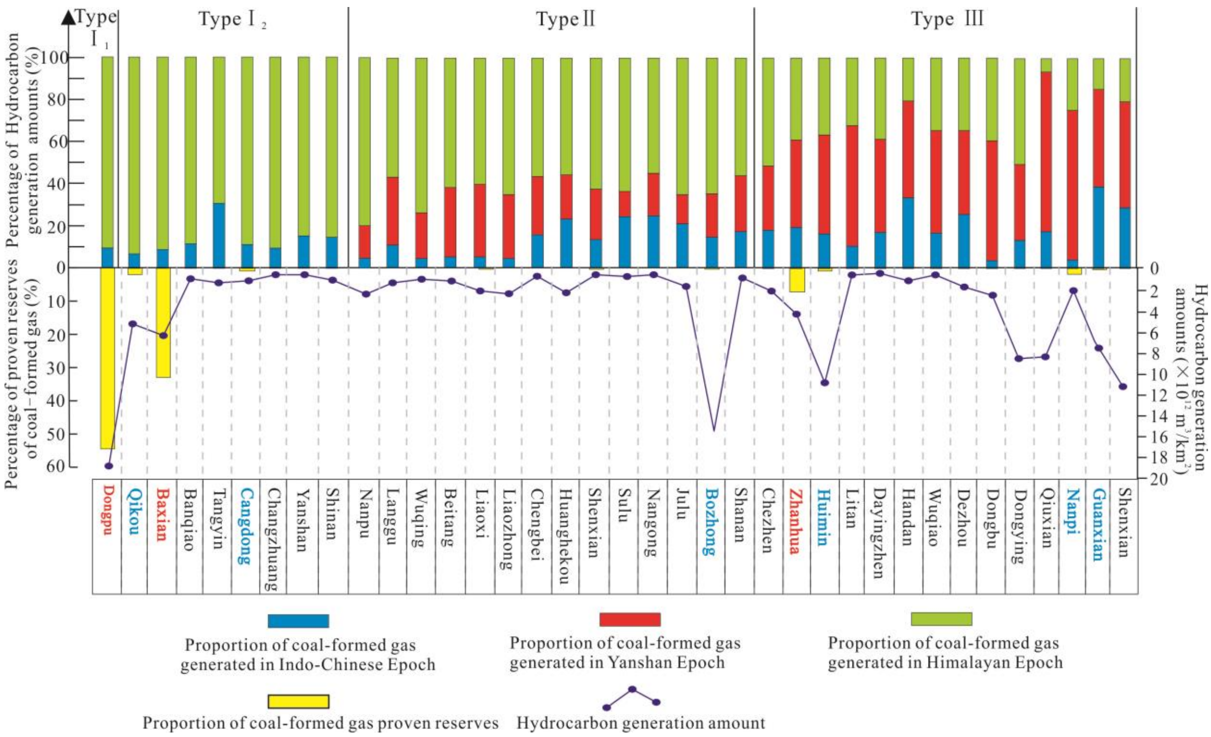


Fig. 9. Chart demonstrating the cumulative hydrocarbon production, proportion of the hydrocarbon production in three tectonic evolution stages (the Indosinian epoch, Yanshanian epoch and Himalayan epoch respectively) and proven reserves of coal-derived gas of different Depressions in Bohai Bay Basin.

5.2 Fault-cap rock dual control vertical distribution of coal-formed gas

As mentioned in Section 1.1, multiple sets of caprocks developed vertically in the Bohai Bay Basin. Commonly, the sealing property of caprocks is the most direct and fundamental factor that controls the vertical distribution of natural gas in different intervals (Faulkner et al., 2010; Çiftçi et al., 2013; Clemenzi et al.,2015; Pei et al., 2015; Mohammedyasin et al., 2016). However, the Bohai Bay Basin is a faulted basin, and numerous faults developed in the Paleozoic to Cenozoic system which affect the sealing integrity of caprocks to different extent (Jiang et al., 2015). In this case, the vertical distribution of natural gas depends not only on the sealing property of the caprocks, but also on the connecting capacity of a fault for hydrocarbon migration over geological time scales (Aydin, 2000; Zhang et al., 2011; Brogi et al., 2015). In other words, the fault-caprock sealing capacity has a major influence on the vertical distribution of natural gas.

The statistical results show that there are three types of faults in the coal-formed gas fields in the Bohai Bay Basin, correspondingly forming four types of fault-caprock combinations. As for some coal-formed gas fields such as Gubei and Wumaying, there are only few faults being weakly active during the main hydrocarbon generation period. The faults occurred with small displacement in the Paleozoic-Mesozoic system with small displacement and the strata were just partially staggered, which gives a larger probability of a sealing surface being continuous over an entire target storage reservoir in the Paleozoic system. The faults tend to be vertically sealed, and the coal-formed gas in these areas usually demonstrated as pattern B or pattern C vertical enrichment. For the faults developed in the coal-formed gas field such as Suqiao-Wen'an, even though the faults broke through the Cenozoic-Paleozoic strata, the fault were weakly active with small displacement, and the sealing surface kept continuous in the Paleozoic system. The gas is most likely to accumulate as Pattern B. However, for some gas field, such as Wenliu and Beidagang, the faults developing in these areas usually continued to be strongly active during the main hydrocarbon generation period. On one hand, the strata on the two walls of the faults were completely staggered by the fault, thus the sealing integrity of a caprock system were also damaged; on the other hand, the fault connects the reservoir on the footwall of the fault and the source rocks on the hanging wall of the fault, thus can provide an effective channel for the vertical transporting of the generated natural gas. The natural gas would migrate vertically along the fault, and the tends to form the A_1 or A_2 vertical enrichment pattern (Fig.10). Overall, the fault-caprock combination show an obvious correspondence with the vertical enrichment pattern of coal-formed gas. Thus, the fault and caprock dual control the vertical distribution of natural gas in different intervals.

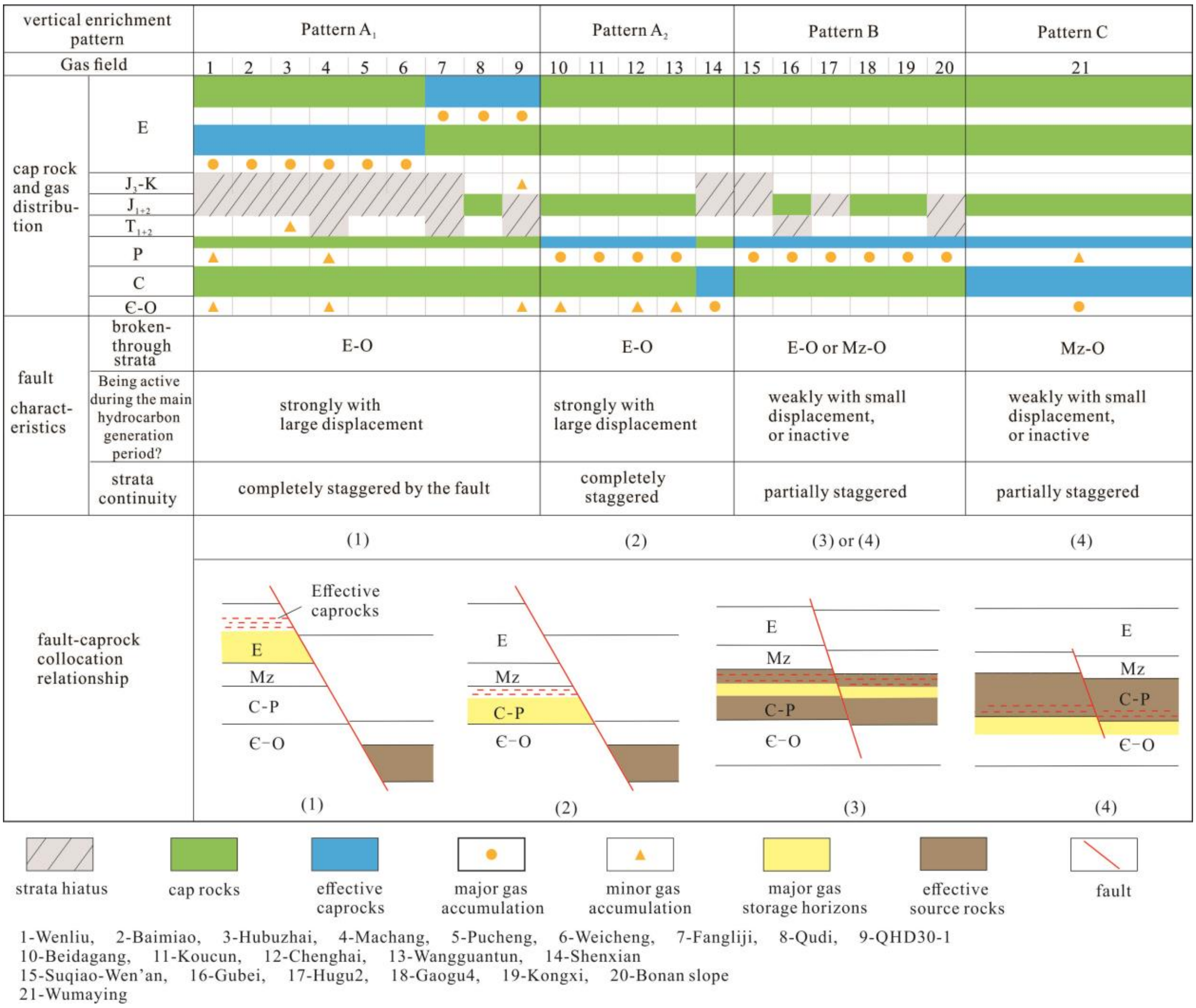


Fig. 10. Diagram showing the relationship between fault-caprock collocation relationship and vertical gas distribution.

Taking the six typical coal-formed gas deposits, including Wenliu, Hubuzhai and Machang gas field as the main analysis areas, the vertical sealing property at the conjunction site of fault and cap rock was quantitatively analyzed based on the Fault Opening Index (FOI) proposed by Zhang et al (2011). The calculated points are shown in Figure 11B. The results show that for the coal-formed gas fields in the Bohai Bay Basin, when FOI>0.96, the opening and closing status of the breakpoints was identified as clearly open because of the presence of hydrocarbon showing as "reservoirs above and below the counted point both contain hydrocarbons" or "reservoirs above the point contain hydrocarbon and those below the point do not" (Fig.11A). When FOI $\leq$ 0.96, the reservoirs below the counting points contain hydrocarbons and the ones above do not, illustrating that the fault at these points remains closed and the coal-formed gas cannot transport through these points to the reservoirs above them (Fig. 11A). The results can perfectly explain the differences in the vertical enrichment characteristics of various coal-formed gas fields in the basin, that is, for areas that are not damaged by faults or the fault are weakly faulted in the duration of hydrocarbon generation, it is more likely to form the coal-formed gas fields of pattern B or pattern C vertical enrichment due to the lack of vertical transport paths. However, for the fault-damaged area, the vertical opening and closing of the fault control the vertical enrichment of coal-formed gas fields, and the coal-formed gas tends to accumulate in the reservoir below the breakpoint with the FOI less than 0.96.

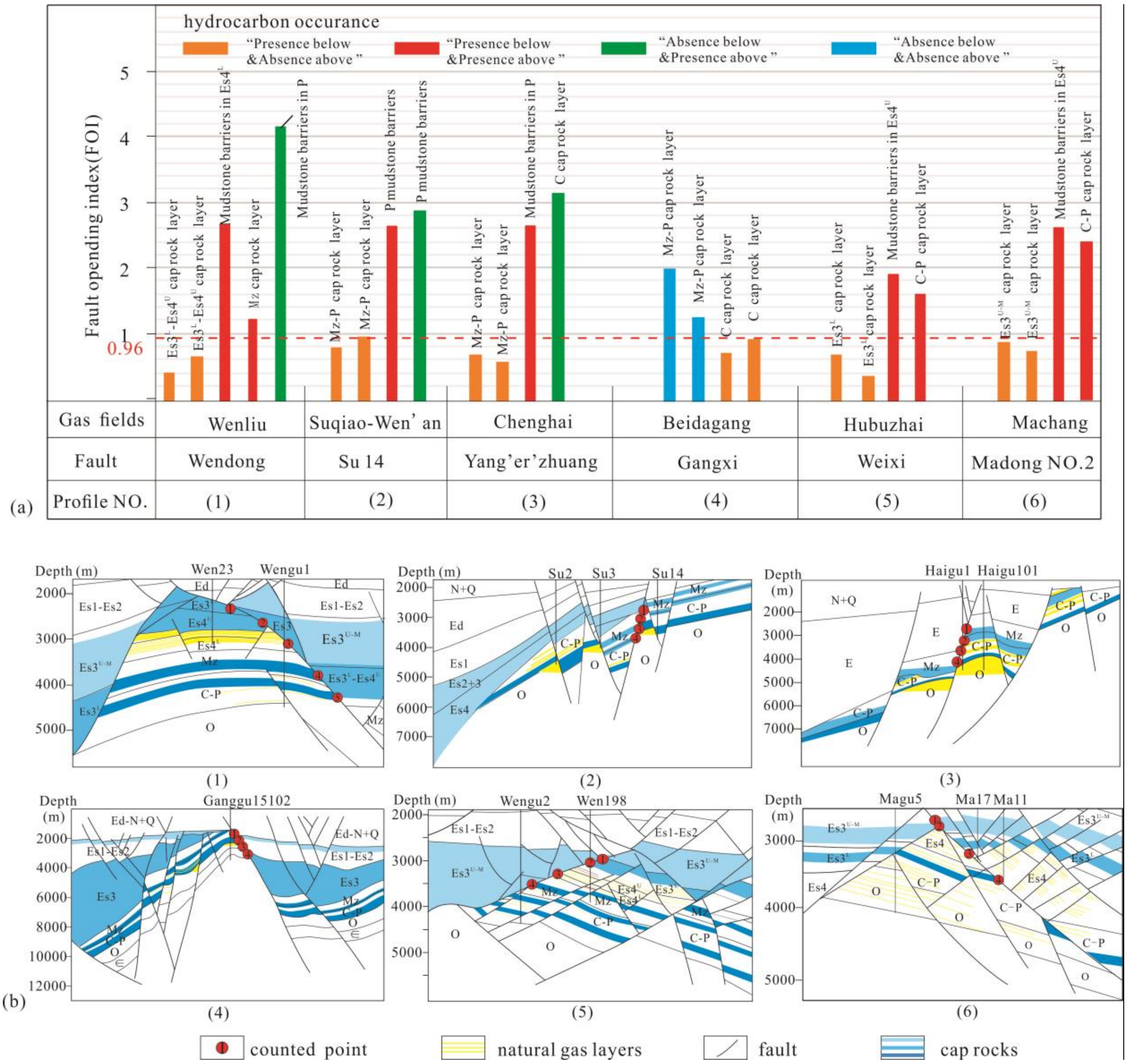


Fig. 11. Relationship between the vertical sealing property of faults and the vertical distribution of coal-formed gas.

(a) Bar chart illustrating the Fault Opening Index of the main faults in the major coal-formed gas deposits in the Bohai Bay Basin; (b) Major coal-formed gas deposit profiles showing the location of calculated points.

6 Summary and Outlook

From all the reviews shown above, the typical characteristics of coal-formed gas generated from the Permo-Carboniferous coal measures in Bohai Bay Basin can be summarized as the following aspects.

(1) Due to the multi-stage tectonic movements in Mesozoic and Cenozoic, the original widely-distributed Permo-Carboniferous coal measures were seriously eroded and finally rifted into approximately 40 isolated source rock kitchens. The source rocks in different depressions present differential thermal evolution and hydrocarbon generation history. Some of them are characterized by late hydrocarbon generation (type □ and type □), while the others are featured by early hydrocarbon generation (type □).

(2) The coal-formed gas deposits are generally small in scale in the Bohai Bay Basin, which is not like the Ordos Basin and Qaidam Basin where many large-sized coal-formed gas fields related to the Permo-Carboniferous source rocks have been discovered (Fang et al., 2016). All the coal-formed gas deposits found in Bohai Bay Basin are middle-sized or small-sized, with the proven reserves ranging from 0.002 to $149.4\times10^8 m^3$. Among them, the Wenliu gas field has the largest proved reserves of $149.4\times10^8 m^3$. The coal-formed gas deposits are limited in the Permo-Carboniferous residual regions and mainly distributed in the areas where the hydrocarbon generation intensity of Carboniferous-Permian is greater than 100×10^4 t/km^2. Besides, over 80% of the proved coal-formed gas are located in the type I depressions which have large amount of cumulative hydrocarbon generation.

(3) The coal-formed gas generated from the Permo-Carboniferous have multiple vertical enrichment patterns

and corresponding accumulation models. The areas where faults are always inactive, such as the gentle slope zones and the deep sag zones, tend to form the gas deposits with the "inner-source" or the "below-source" enrichment pattern and accumulation model. However, in the areas where faults hold strong fault activity, such as the central uplift belts in a depression, the steep slope zones and the uplift belt between depressions, the coal-formed gas tend to accumulated as the "above-source" model. The vertical distribution is mainly controlled by the fault activity and the fault-cap rock configuration. The gas probably accumulated in the reservoir below the cap layer with the Fault Opening Index value less than 0.96.

Even though the continuity of Permo-Carboniferous is poor and the area where source rock kitchen occurred is small, the Permo-Carboniferous source rocks still has considerable cumulative hydrocarbon generation intensity in the whole basin. Furthermore, many large depressions, including the Dongpu, Guanxian, Qiuxian, Shenxian Depression in Linqing sub-basin, the Baxian Depression in Jizhong sub-basin, the Dongying, Huimin Depression in Jiyang sub-basin, the Qikou Depression in Huanghua sub-basin, and the Bozhong Depression in Bozhong sub-basin, hold a large amount of cumulative hydrocarbon production (Fig. 9). All the data illustrates the potential of forming large and medium-sized coal-formed gas fields in Bohai Bay Basin.

According to the characteristics of the Permo-Carboniferous coal-formed gas deposits in Bohai Bay Basin discussed above, the exploration in different areas should be targeted at certain types of gas deposits. To be specific, for the type □ depressions with early hydrocarbon generation characteristics, the slope zones and deep sag zones are beneficial for the preservation of coal-formed gas formed in the early stage, thus these areas would be potential exploration area for the "Inner-source" or "Below-source" gas fields. For the type □ depressions characterized by late hydrocarbon generation, the areas where faults hold strong fault activity might be the exploration targets with great economic feasibility.

Acknowledgements

The authors gratefully acknowledge the financial support from the National major projects (Item No.2016ZX05006-003). Appreciations are also given to the following institutions: Shengli Oilfield Company and Zhongyuan Oilfield Company of Sinopec, Dagang Oilfield Company and Huabei Oilfield Company of PetroChina. These companies provided all the related geological and exploration data.

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